

IMPROVEMENT OF SPACE SHUTTLE MAIN ENGINE LOW FREQUENCY ACCELERATION MEASUREMENTS

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ABSTRACT

The noise floor of low frequency acceleration data acquired on the Space Shuttle Main Engines is higher than desirable. Difficulties of acquiring high quality acceleration data on this engine are discussed. The approach presented in this paper for reducing the acceleration noise floor focuses on a search for an accelerometer more capable of measuring low frequency accelerations. An overview is given of the current measurement system used to acquire engine vibratory data. The severity of vibration, temperature, and moisture environments are considered. Vibratory measurements from both laboratory and rocket engine tests are presented.

KEYWORDS

Low frequency, data quality, noise, noise floor, signal-to-noise ratio, accelerometer, damping, sensitivity, vibration, random, sinusoidal, blade wake, shock, cryogenic, piezoelectric, variable capacitor.

BACKGROUND

Ground test vibration measurements on the Space Shuttle Main Engine (SSME) do not adequately measure hardware accelerations below approximately 400 Hz. This is of concern because all of the larger engine

components (ducts, turbopumps, exhaust nozzle, etc.) have significant resonances below that frequency. Comparisons to straining data and reasonableness checks indicate that comparable accelerometer data often over-predict accelerations in this frequency range by an order of magnitude or more. Engineering use of such measurements can result in overly conservative fatigue life predictions of engine component hardware. The fundamental concern, therefore, is that the accelerometer measurements are overly conservative.

Measurements of low frequency dynamic accelerations generated by the SSME are difficult because of the severity of the self-induced engine environments:

- The vibration environment extends over a wide frequency range and is composed of broadband random vibrations induced by turbulent flow of propellants and fluctuating pressures due to propellant combustion. There is also significant contribution due to concurrent sinusoidal excitations. These sinusoidal excitations are generated by blade and vane wakes within the turbomachinery and vary with turbopump speed.
- In addition to steady-state vibration, there are significant transient vibration events. At engine start, a shock wave

forms in the throat of the main nozzle and progresses with 'nonsymmetrical motion the length of the nozzle, finally detaching itself at the exit plane. There are also shock waves generated by the preburner combustion chambers due to normal engine start-up transients as well as shocks caused by combustion instabilities.

- The temperature environment is severe. Structural temperatures on external surfaces range from hundreds of degrees above ambient to cryogenic temperatures that are hundreds of degrees below. Although the SSME produces combustion exhaust gases that are thousands of degrees hot, most of the primary structure is very cold during operation because the SSME's propellants are cryogenic. Liquid hydrogen is the fuel and liquid oxygen the oxidizer. These propellants significantly reduce the temperature of lines, ducts, and pumps, etc. through which they flow. Additionally, the liquid hydrogen is routed through passages throughout the engine, keeping it cold to maximize its strength.

OVERALL APPROACH TO THE REDUCTION OF LOW FREQUENCY NOISE

The overall approach to improve the quality of low frequency acceleration data acquired on the SSME involves a thorough review of the acquisition system. An end-to-end review includes a review of accelerometers, cabling, connectors, filters, amplifiers, analog-to-digital converters, and tape recorders. Table 1 is a matrix that presents an improvement plan that considers all of these. It identifies the

evidence supporting or contradicting the potential for each of these items being a significant contributor to low frequency noise. A review of this matrix reveals that there is no obvious source; every potential source has evidence both supporting and contradicting it as a contributor. The intent of this plan is to study each of these items. This study has been initiated and is currently in progress.

The focus of this paper addresses Item 1 of this study. That is, it is assumed that low frequency data quality can be substantially improved with the use of a more specialized accelerometer. Such an accelerometer would significantly increase signal strength and consequently reduce the signal-to-noise ratio.

Others have studied accelerometer signal quality. Barrett [1], [2] discusses sensor selection as well as system considerations for the acquisition of low frequency measurements. Schloss [3] investigates low level (100 micro g), low frequency piezoelectric measurements. He finds that piezoelectric noise is inversely proportional to charge sensitivity. Dauderstadt, et al. [4] present a novel low frequency thermal accelerometer capable of measuring frequencies up to 300 Hz. His concept is to employ a typical seismic mass as a heat sink in close proximity to a constant thermal source. The amount of thermal energy passing into the heat sink varies with the distance to the thermal source, and is measured with thermopiles.

THE BASELINE ACCELEROMETER

The standard accelerometer used for SSME measurements is the piezoelectric Endevco Model 7704-M6. While use of this accelerometer may result in poor low frequency data quality, its application benefits

Table 1. SSME Vibration Measurement Improvement Plan to Reduce Low Frequency Distortion

#	DISTORTION CAUSE	EVIDENCE FOR	EVIDENCE AGAINST	EVALUATION APPROACH	TEST	SIGNAL PATH	CONTROL MEASUREMENT	EXPECTED RESULTS	ENV. COND.	CORRECTIVE ACTIONS
1	Accel unstable because excited at natural frequency	Measured sinusoid coincident with resonant frequency	Controller accels exhibit same distortion	Evaluate Piezoresistive & Capacitive accels w high damping or no coincidence of Fn w harmonics	Install Piezoresistive and Capacitive accels on SSME and compare results w piezoelectric accels	Evaluate with and without line driver before the Drag line	Shock accels, strain gages, Alpha strain sensors, Laser vibrometer?	Undistorted data < 10 khz	Cryo/Hot sensitivity and impedance	Procure and calibrate Piezoresistive and Capacitive accels
2	Amplifier saturated by high-frequency rotational harmonics	Resonant frequency coincidence worsens distortion	Controller accels exhibit same distortion phenomena	Evaluate active-filter roll-off and multiple filters amplifier saturation	Compare SSME signals w sharper filters and multiple filters vs current hardware	Evaluate with and without line driver & filter before the Drag line	Shock accels, strain gages, Alpha strain sensors, Laser vibrometer	Undistorted data < 10 khz	Cryo/Hot sensitivity and impedance	Procure sharper, higher dynamic-range and multiple filters
3	Active filters saturated by high-frequency rotational harmonics	Resonant frequency coincidence worsens	Controller accels exhibit same distortion phenomena	Evaluate non-saturating circuitry, using SPICE-based simulation	Compare SSME signals w non-saturating circuitry	Evaluate with and without line driver & filter before the Drag line	Shock accels, strain gages, Alpha strain sensors, Laser vibrometer	Undistorted data < 10 khz	Cryo/Hot sensitivity and impedance	Design/develop non-saturating circuitry
4	Cross-Talk in Amplifiers	Controller accel data distorted w/no high vibration	Only isolated cases found	Separate amplifier racks for specific accels	Compare SSME signals w terminated cables and separated amplifiers	Evaluate with and without line driver before the Drag line	Terminated cables and separated amplifiers	Undistorted data < 10 khz	Any	Design and develop proper termination
5	Cable Length	Capacitive loading, attenuation	Unknown	Install in-line amplifiers	Compare SSME signals with various length cables and configurations	With and without line driver before the Drag line	Current cable length and configuration	Undistorted data < 10 khz	Any	Procure different length cables
7	Digitization Noise	FASCOs: 2 ⁿ -12 RASCOs: 2 ⁿ -16 Facility: ??	Aliasing, low signal	Evaluate higher-resolution and present digitizers	Compare higher-resolution and present digitizers	With and without line driver before the Drag line	Magnetic Tape Data	Undistorted data < 10 khz	Any	Procure a higher resolution digitizer
8	Data Acquisition/Processing Distortion	Strongest evidence in PSDs		Evaluate a better data acquisition system with present system	Compare a better data acquisition system with present system	With and without line driver before the Drag line	Magnetic Tape Data	Undistorted data < 10 khz	Any	Procure a better data acquisition system
9	Pump (real) low-frequency vibration	Observed constantly	Strains contradict g's. Displacements would be visible	Use mechanical filters	Install mechanical filters on SSME and compare results	With and without line driver before the Drag line	Shock accels, strain gages, Alpha strain sensors, Laser vibrometer	Low g's at low frequencies	Cryo/Hot sensitivity and Impedance	Design and fabricate mechanical filters

from its more superior characteristics. These include excellent cryogenic capability, very good frequency response at higher frequencies, and extreme durability.

THE SEARCH FOR A BETTER ACCELEROMETER

Rocketdyne engineers involved in acquiring acceleration data were asked to identify other accelerometers (or other transducers) that might improve the SSME low frequency data quality. A “brainstorming session” was held to consider the possibilities. Table 2 presents the results of this session. Six different transducers were compared against the Endevco 7704-M6. Seven important transducer characteristics were rated. The values presented in Table 2 were arrived at by consensus using the available knowledge at the time of the meeting. A “+1” value shows the characteristic of the considered transducer would be expected to be somewhat better than that of the reference accel. A “+2” value shows the transducer being considered would be expected to be much better. Negative values were assigned similarly. A value of zero means no appreciable difference would be expected.

THE ENDEVCO MODEL 7290A-100 VARIABLE CAPACITOR ACCEL

As indicated in Table 2, the characteristics of the variable capacitor accel (Model 7290a) [5] compare favorably to the Model 7704 piezoelectric (our standard accel). Other session participants have extended consideration for the alternates; however, the remainder of this paper presents characteristics of the Model 7290a-100 variable capacitor accel compared to the standard 7704-M6 accel and considers their performance on the SSME.

Sensitivity

One of the most important attributes of the Endevco Model 7290a-100 variable capacitor accel is its relatively high measurement sensitivity. The 7290 accel has a measurement sensitivity of 20 mV/g. This is approximately 15 times greater than the equivalent sensitivity of the 7704. This feature can greatly improve the signal-to-noise (S/N) ratio on acquired data. (The 7704 is a piezoelectric charge accel with a 12 pC/g charge sensitivity. Converting the 12 pC/g sensitivity to voltage sensitivity by dividing it by the total in-use capacitance of 10,000 pF yields an equivalent voltage sensitivity of 1.3 mV/g.)

Damping

Another important characteristic is damping of the accel at its sensor resonant frequency. The damping of the 7704 piezoelectric accel has been measured by Rocketdyne to be less than 1.0% of critical. By comparison, the Model 7290 has very high sensor damping. The active sensing element is pneumatically damped to approximately 60% of critical. This provides two significant advantages. The sensing element is not significantly excited at resonance, and because the damping is pneumatic, the damping characteristics change very little over a wide range of temperatures.

Resonant Frequency

The resonant frequency of the 7290's sensing element is low (approximately 4500 Hz) compared to that of our standard accel's (approximately 36,000 Hz). This precludes the use of the 7290 for measuring frequencies

Table 2. Kick-Off Meeting: Transducer Brainstorming Assessment

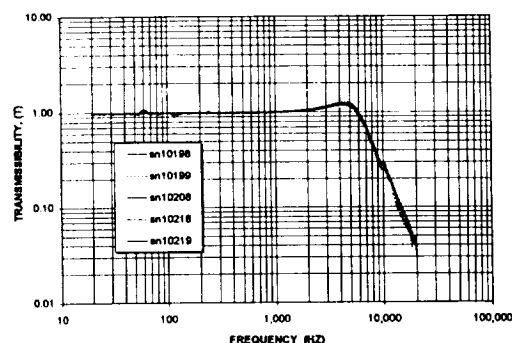
Transducer System	Sensitivity	Thermal Limitation	Damping	Mounting Capability	High Freq Capability	Survivability Today	Accel Resonance	Sum Total
Reference: Current 7704 Accel	0	0	0	0	0	0	0	0
-----	-----	-----	-----	-----	-----	-----	-----	-----
PCB Piezoelectric	2	1	0	0	0	-1	0	2
Variable Capacitance	2	-1	1	-1	0	-1	2	2
7704 Ceramic (New)	1	0 ?	0	0	0	0 ?	0	1
Vel Pick-up (PCB)	2	0 ?	0	0	-1	-1	0	0
Piezo- Resistive	2	-2	1	0	-1	-1	2	1
Servo Accel (Quartz flex)	3	-1	1	?	?	-3	?	0

over the entire 20 to 10,000 Hz range measured with the standard accel. However, there are two advantages of having a low resonant frequency coupled with good viscous damping. For the same amount of damping, a lower sensor element resonant frequency results in lower overall output (Grms) because the bandwidth of the resonance is smaller at lower frequencies. Also, at frequencies greater than the resonant frequency, significant sensitivity loss occurs which minimizes the contribution of these high frequencies to the overall signal output (Grms) by the accel's sensor. This permits the accel's internal amplifier to function without clipping in stronger high frequency content environments and allows the external amplifier gain to be set lower because of the lower intensity signal it receives. These effects help the Model 7290 to function successfully in SSME locations of stronger steady-state vibration.

While the 7290 accel design does have the benefit of a highly damped sensor resonance, and its low resonant frequency does have the above described advantages, there is some amplification of the measured environment between approximately 1000 Hz and 6000 Hz (Figure 1). This amplification limits accurate measurements with this accel to frequencies less than 1000 Hz.

Shock Survivability

As previously mentioned, strong pressure induced shocks occur during SSME startup. Peak acceleration levels of 1000 g's are common, with maximum expected levels approaching 4000 g's. The specification survivability of the 7704 accel is 10,000 g's. This is more than adequate for even the maximum expected SSME levels. The shock specification for the 7290a-100 is also



*Figure 1. Sine Sweep Resonance Checks.
Overlay of five 7290a-100 accel's.*

10,000 g's. Additionally, a study conducted by Endevco [6] found that these accels can survive up to 90,000 g's with only minor performance degradation.

Ice, Frost, And Moisture

Because liquid hydrogen and liquid oxygen are used as propellants, and because liquid hydrogen is also used to cool parts of the engine to maintain structural integrity, most of the external surfaces of the engine are cryogenic. (In fact, uninsulated surfaces that are in contact with liquid hydrogen are cold enough to liquefy the external ambient air that comes in close proximity.) As a result, accels mounted to these surfaces not only are exposed to very cold temperatures, but must also tolerate being iced-up or frosted-over. After the engine is shutdown, the ice and frost melt and result in moisture and humidity. The sensor of the 7704 is mounted in a hermetically sealed stainless steel case that precludes any possibility of damage from icing, frost, or moisture contamination. The circuitry and the sensor of the Model 7290 are mounted together in an inner stainless steel container that is hermetically sealed by welding. This container is mounted into an aluminum outer case that is then epoxy sealed.

LAB TEST RESULTS

Figure 1 (previously mentioned) is a transmissibility plot of the output from five 7290 accels induced by an ambient 5 g sine sweep. These transmissibility curves show the repeatability and very low amplification at the 4500 Hz accel resonant frequency.

Cryogenic Tests

Cryogenic vibration tests have also been conducted at Rocketdyne on the 7290a-100 variable capacitor accelerometer. Figure 2 is an overall photograph of the test set-up, a cryogenic oven mounted over an electromagnetic shaker. Temperatures are achieved by flowing liquid nitrogen through a copper tube heat exchanger. Figure 3 is a close-up showing a 7704 and a 7290 accel mounted for testing. (The oven door has been removed for both of these photographs.)

The overall sensitivity of the 7290 compared to the 7704 has been assessed with this laboratory set-up. The broadband random environment of Figure 4 was applied for a series of temperatures from ambient to -300 F. This environment was prepared in an attempt to simulate engine vibration levels. Constant velocity is assumed from 5 to 710 Hz, resulting in a positive slope of 6.02 dB/Octave. Constant acceleration is assumed from 710 Hz to 7000 Hz. Both accels were mounted side-by-side. The overall Grms response from 0 to 2000 Hz is presented in Figure 5. It can be observed that the 7704 has only a slight loss of sensitivity at colder temperatures. By comparison, the 7290's sensitivity is almost constant to -150 F., decreasing moderately to -225 F., then rapidly dropping to near zero at -265 F. The 7290

gave almost no response at -300 F., but recovered fully at approximately -265 F. during the up-ramp in temperature. This characteristic was first thought to be a unique anomaly. However, additional testing revealed that this phenomenon occurred repeatedly on this accel and on other 7290's, the dropout temperature always occurring between -255 F. and -265 F. The cause has not been determined. One possibility is that it is an intrinsic property of the doped silicon used to fabricate the active sensing element. In any case, no degradation of performance of these accels has been noted as a result of operating at these temperatures. (It is noted here that the difference in response between the 7290 and the 7704 for temperatures above -150 F. are attributed to inaccurate pre-test calibration and a slight response amplification above 1000 Hz as the 4500 Hz resonance of the 7290 accel is approached. Conversely, at frequencies above 4500 Hz an attenuation of response is observed relative to the 7704 accel.)

The frequency response of both accels as a function of temperature is also obtained during these tests. Figures 6 and 7 present these results. Both accels track the environment (Figure 4) very well. Both produce credible measurements down to as low as 10 Hz. (Below 10 Hz there is difficulty with the acquisition system. A major shaker assembly resonance amplifies the data at 3200 Hz.)

The performance of the 7704 at low frequency is surprising good. Even though the applied laboratory environment is the most severe that could be produced in amplitude, frequency content, and temperature, it is nevertheless concluded that the severity of the engine-operating environment was not adequately simulated. In particular, the high frequency content that would strongly excite the 7704's crystal resonance could not be generated.

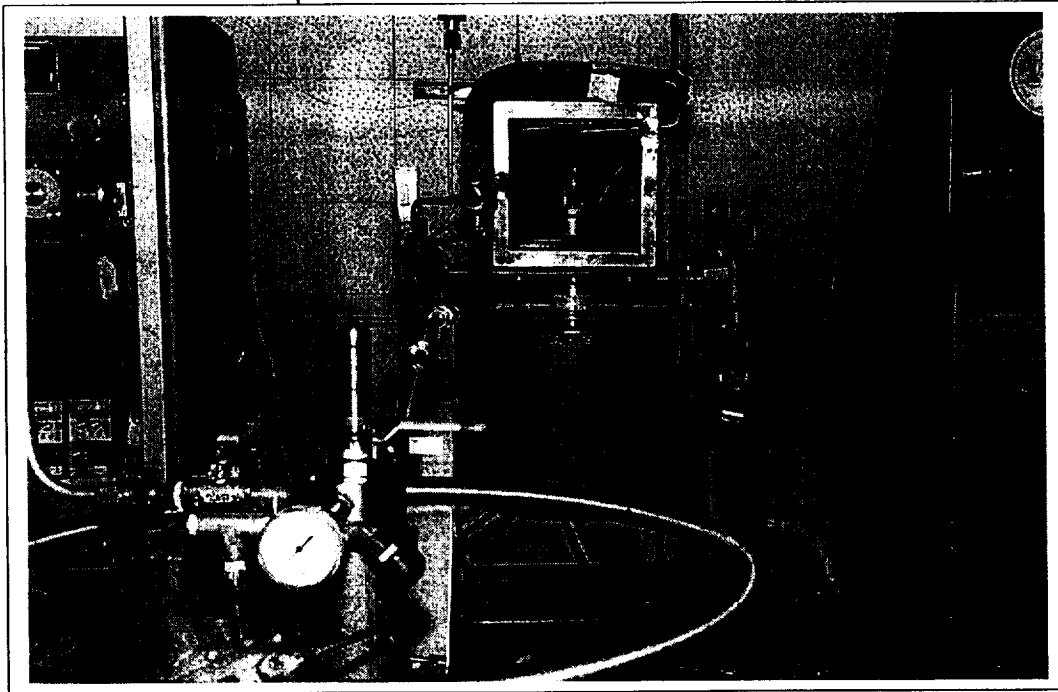


Figure 2. Test Setup for Cryogenic Laboratory Tests. A cryogenic oven is mounted over an electromagnetic shaker. A shaker head extension fixture passes through the bottom of the oven.

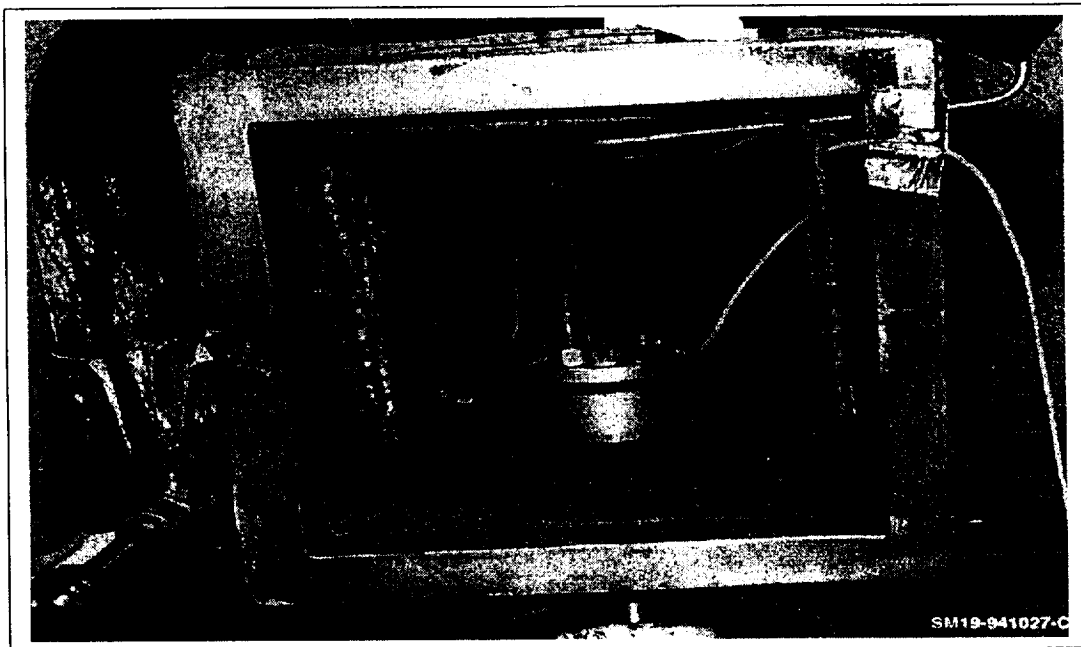


Figure 3. Close-up view of cryogenic test setup. Model 7704-M6 accel (left) and Model 7290a-100 accel (right) mounted to top of shaker extension fixture.

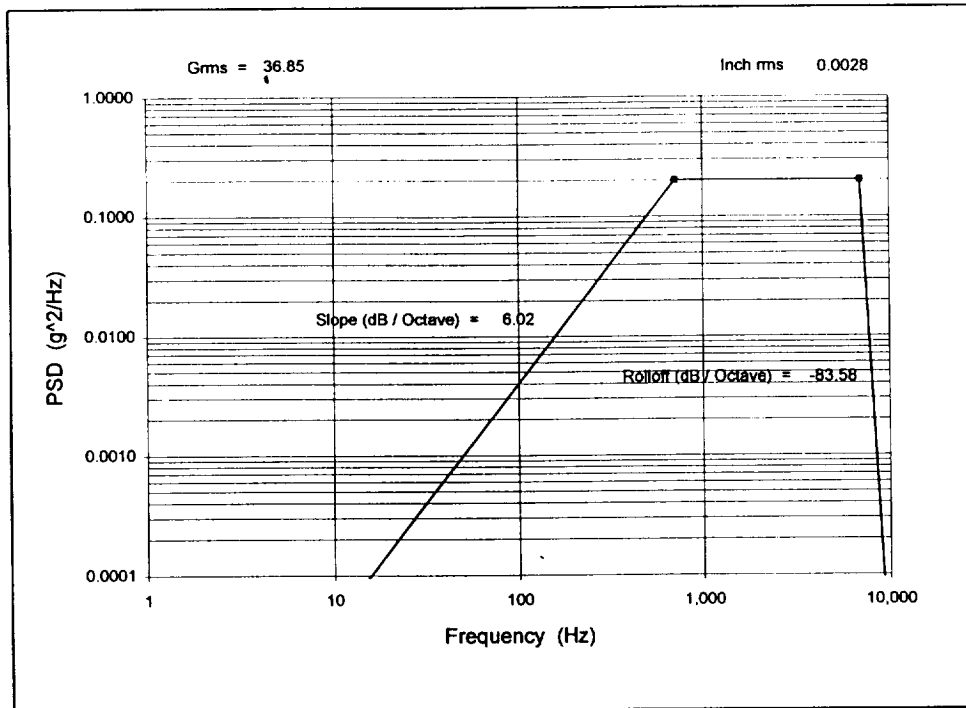


Figure 4. Input Test Spectrum
Constant Velocity from 5 Hz to 710 Hz plus Flat Random from 710 Hz to 7000 Hz

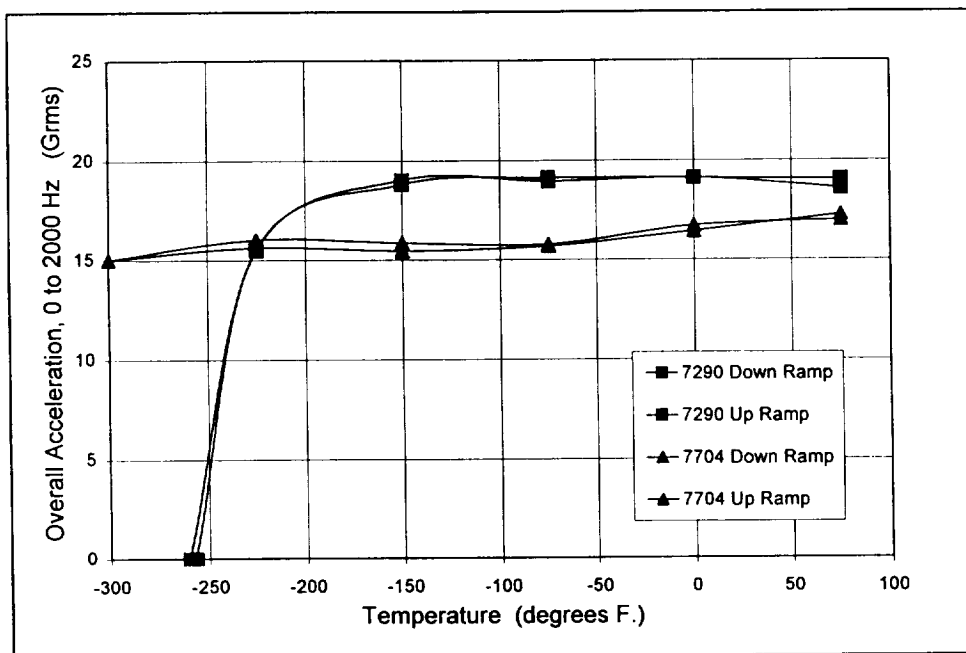


Figure 5. Broadband Random Test (5 to 7000 Hz Excitation)
Endevco 7704-M6 and 7290a-100 Accels
(adjusted for base excitation variation)

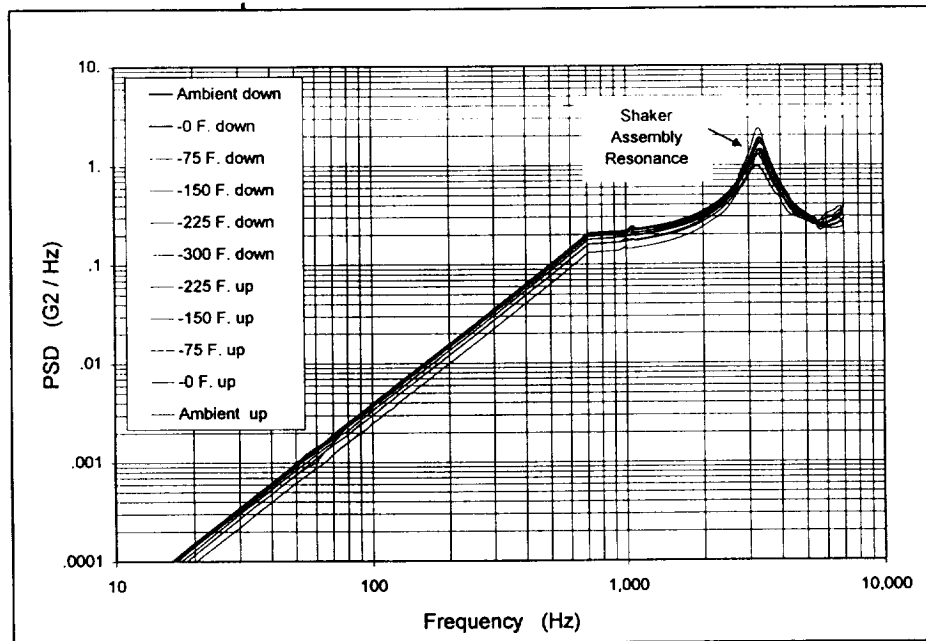


Figure 6. Response of Model 7704-M6 Accel to Simulated SSME Random Vibration Environment over a Range of Cryogenic Temperatures

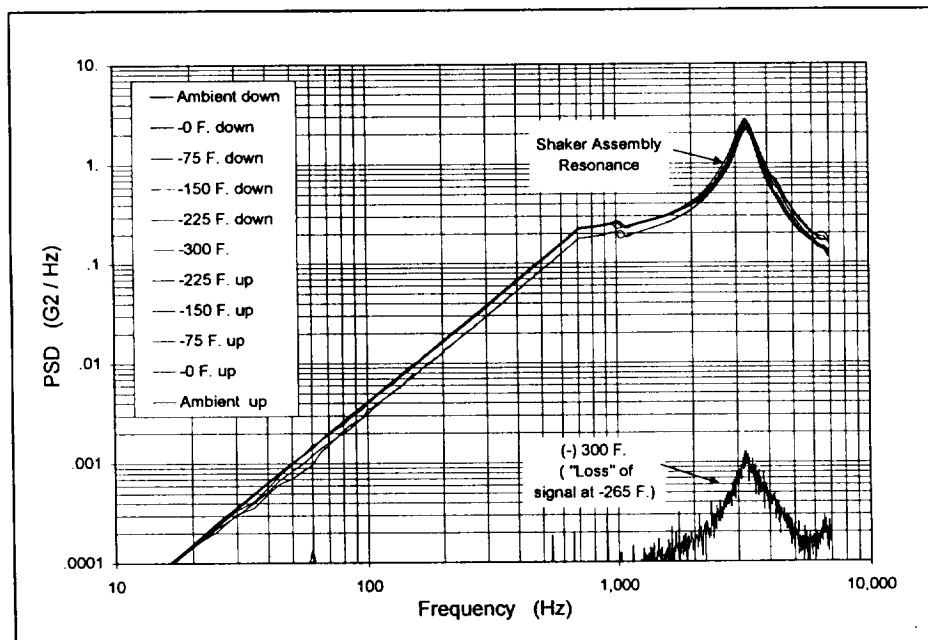


Figure 7. Response of Model 7290a-100 Accel to Simulated SSME Random Vibration Environment over a Range of Cryogenic Temperatures

OPERATIONAL ENGINE TESTS (HOTFIRE TESTS)

7290's have been mounted on SSME's during operation engine ground tests. Figure 8 shows a typical installation of a 7290 on an engine. In this installation it is mounted on a standard SSME 1" steel mounting cube that is adhesively bonded to a flange.

Figures 9 and 10 compare engine vibration measurements of a 7290 to a 7704. These accels are mounted near each other on the forward end of the main nozzle. Below 500 Hz the 7290 produces a signal with as much as 20 dB less noise than the 7704. Between 500 Hz and 1200 Hz the two accels have virtually identical response. Between 1200 Hz and 5000 Hz the 7290 has a response that is as much as 3 dB higher than the 7704. (It should be noted that the manufacturer specifies the measurement range of the 7290 as 0 Hz to 1000 Hz, so measurement accuracy at frequencies greater than 1000 Hz is not expected.)

Measurements with the 7290 have also been made at other engine locations. When mounted to the turbine flange of the high pressure fuel pump, a location noted for its strong vibration levels, the accel quickly failed. Another accel was installed at this location, and it also failed. To determine the cause of failure, the accels were brought to the manufacturer for examination. The failures were found to be due to the breakage of an internal wire. In both cases, the longest of the three wires routed from the variable capacitor sensor to the internal circuit board failed. Both wires failed in the same location. After examining the breaks, it was concluded that the failures were not a manufacturing defect. Further investigation

showed that the first resonant frequency of these wires was excitable by 73N and 78N turbine blade wakes of the turbopump they were mounted on. Fortunately the circuit board design permitted a re-routing of the failed wire to reduce its length. Replacement accels with a shortened wire have been extensively tested, and have not failed.

Vibration measurements using the 7290's have been made during dozens of engine tests on different engine components. Unfortunately, the quality of the low frequency data obtained was not consistent. Data quality varied from fair to poor most of the time. Only occasionally was it excellent. It was not clear why this was occurring. End-to-end checks were performed. Accel installations were checked. Cables were swapped. Connectors were replaced. Tape recorders were changed. Nothing seemed to consistently improve the data quality. Finally, after reviewing a fairly large collection of acquired data, it was observed that data quality was consistently good at lower engine power levels. This had not previously been observed because this type of data is infrequently available and therefore is only a small part of the collected data set. Also contributing to the complications of interpretation was that more frequent observations of data at higher power levels also showed high quality, but not on a consistent basis. This lack of consistency is now believed to be the result of operating the 7290 near its amplitude limit combined with an accel-to-accel variation in this limit.

As a result of the above finding, it was postulated that the quality of the low frequency noise floor was related to engine

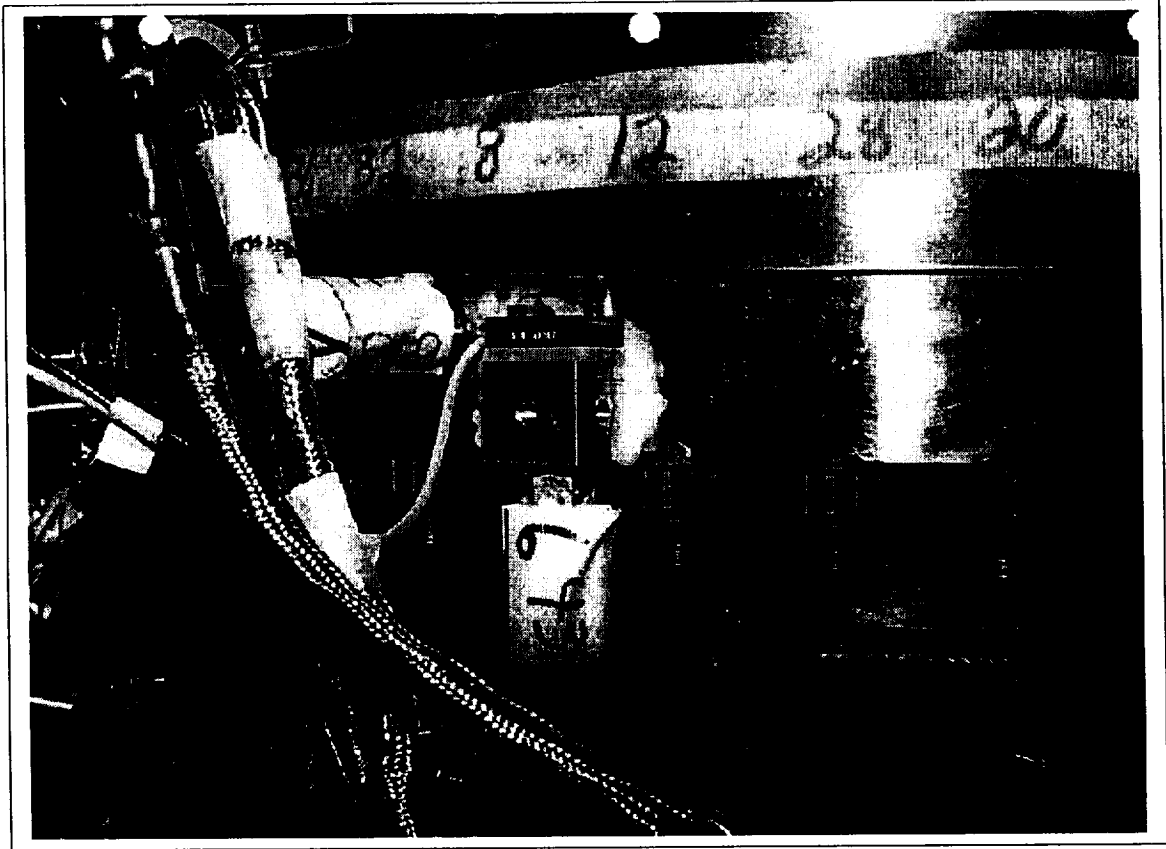


Figure 8. Typical Installation of a Model 7290a Variable Capacitor Accel on the Space Shuttle Main Engine (SSME). The accel (black) is mounted to a 1" steel cube that is adhesively bonded to a turbopump flange. It measures vibration parallel to the turbopump centerline.

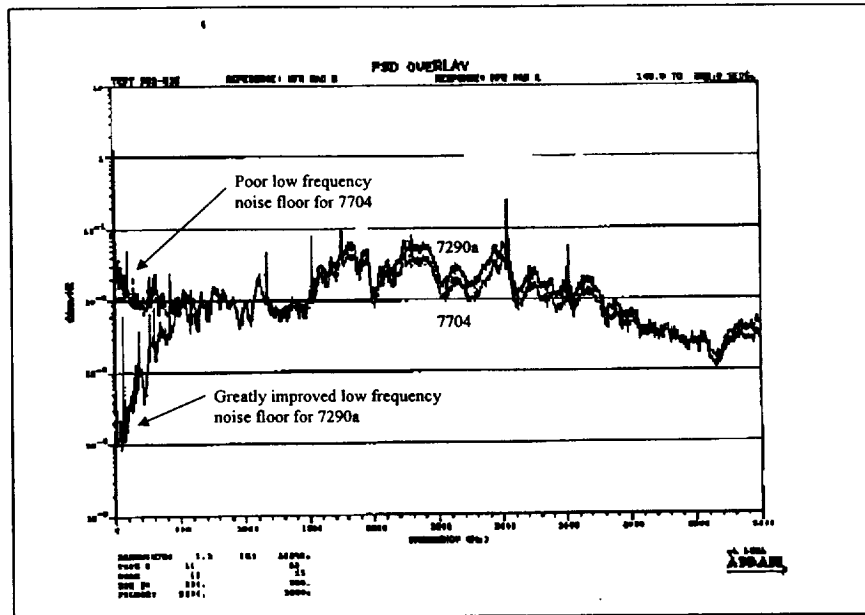


Figure 9. Comparison of Model 7704-M6 and Model 7290a-100 vibration measurements. PSD Overlay: 0 to 5000 Hz. Power Spectral Density versus Frequency. Space Shuttle Main Engine (SSME) operational ground test.

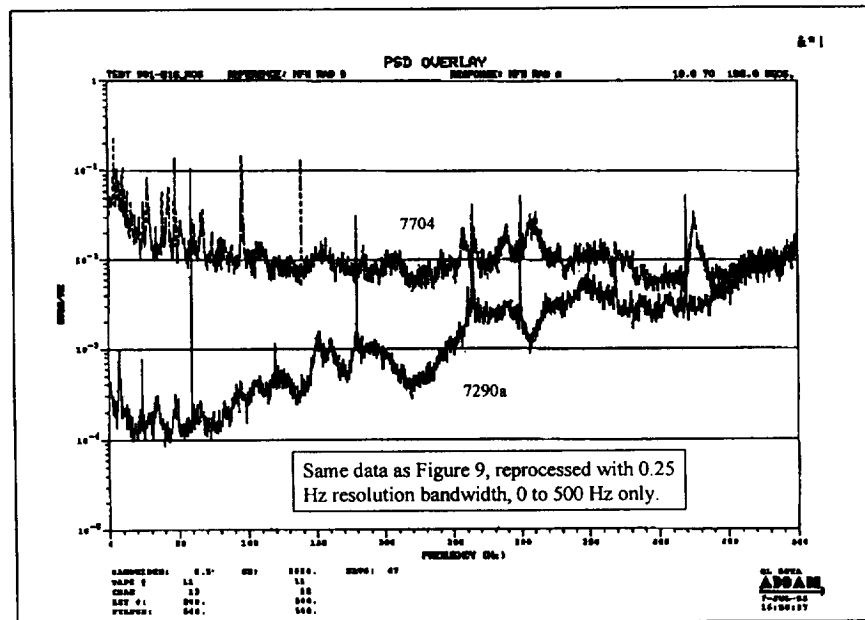


Figure 10. Comparison of Model 7704-M6 and Model 7290a-100 vibration measurements. PSD Overlay: 0 to 500 Hz. Power Spectral Density versus Frequency. Space Shuttle Main Engine (SSME) operational ground test.

power level, and that the 7290 may often be operating beyond its amplitude range. To test this scenario, the overall Grms levels obtained using SSME standard data processing were reviewed. Data acquired in this manner include RMS time-histories and 0 to 5000 Hz power spectral density plots (PSD's). Data was obtained on the Low-Pressure Oxidizer Turbopump (LPOTP) housing during an operational ground test. The standard SSME data processing was considered acceptable because 7290's have a low (approximately 4500 Hz) resonant frequency, so no significant response was expected from higher frequency content such as blade wakes, etc. In order for this data to support the over-driven scenario, equivalent peak g levels that are calculated from the 0 to 5000 Hz PSD's would have to exceed the amplitude range of the 7290 accel. However, review of data acquired in this manner did not confirm the over-driven scenario, but instead showed that 3-sigma and 4-sigma equivalent peak levels were usually well within the operating range of the 7290.

Revisiting the above assumptions, consideration was given to the possibility that the energy content associated with frequencies above 5000 Hz may be a significant contributor to overall response. Therefore, a follow-up investigation with data acquired to 20,000 Hz was performed. The results of this investigation do indeed support the over-driven scenario. Figure 11 presents PSD's and corresponding overall Grms levels with frequency content from 0 to 20,000 Hz. With increasing power level (from 80% to 104%) the 3.5-sigma equivalent peak RMS levels can be seen to exceed the 7290's +/- 170 g mechanical stops and -175 g / + 190 g electrical clipping limits [5]. Of course higher vibration levels are expected solely due to higher engine

power levels, but at increases much less than measured. The maximum nominally expected increase is determined as follows. The power levels of Figure 11 vary from 80% to 104% of full engine power. Using Robert E. Barrett's criterion [7], PSD levels from the highest power level is predicted to be approximately $[(1.04 / 0.8)^{0.5}]^2 = 1.30$ times higher than at 80%. However, increases in the measurements presented in Figure 11 are much greater. From the lowest power level (not over-driven) to the highest (severely over-driven) a factor as much as 1000:1 in acceleration PSD level can be observed at the lowest frequencies. This is orders of magnitude greater than the factor of 1.30 predicted due to power level change alone and is concluded to be the result of an over-driven accelerometer. This finding is consistent with investigations performed by Richard M. Barrett, Jr. [2], who states that high frequency vibration levels can be an indirect source of low frequency noise by overloading the internal amplifier of the accelerometer.

To further support this finding, instantaneous time histories have also been processed. Figure 12 shows portions of the time slices used to generate the Figure 11 PSD's. These time slices indicate an amplitude clipping level at approximately +/- 165 g's peak (330 g's peak-to-peak). Because the external amplifier used in this acquisition was calibrated to acquire full-scale data at 400 g's peak-to-peak, it is concluded that the observed clipping is the result of exceeding the 7290's amplitude range. The observed 165 g clipping level is within 5% of the manufacturer's electrical clipping capability for this accel.

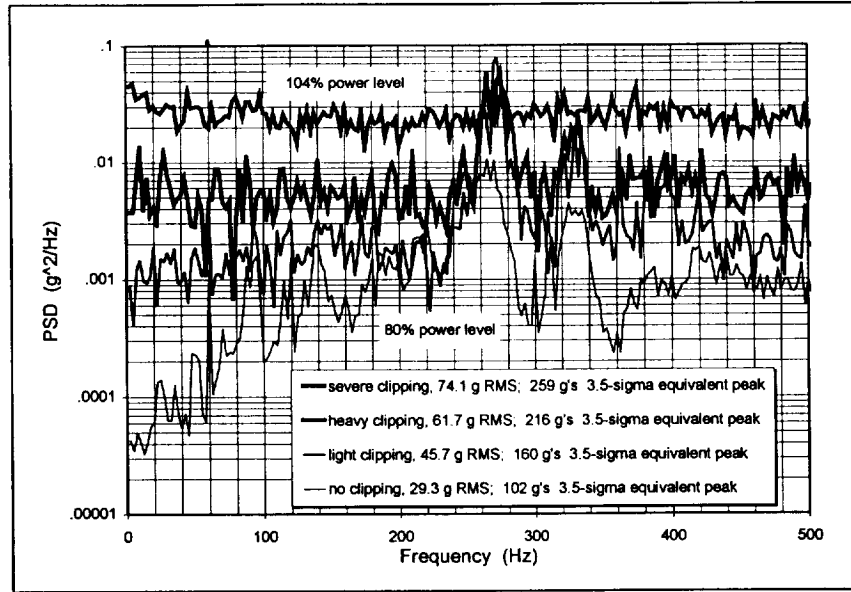


Figure 11. 7290a-100 accel low frequency signal quality for several engine power levels. Overall g RMS values and equivalent peak values include 0 to 20 kHz frequency content. Overlay PSD's for 80%, 99%, 101% and 104% power levels.

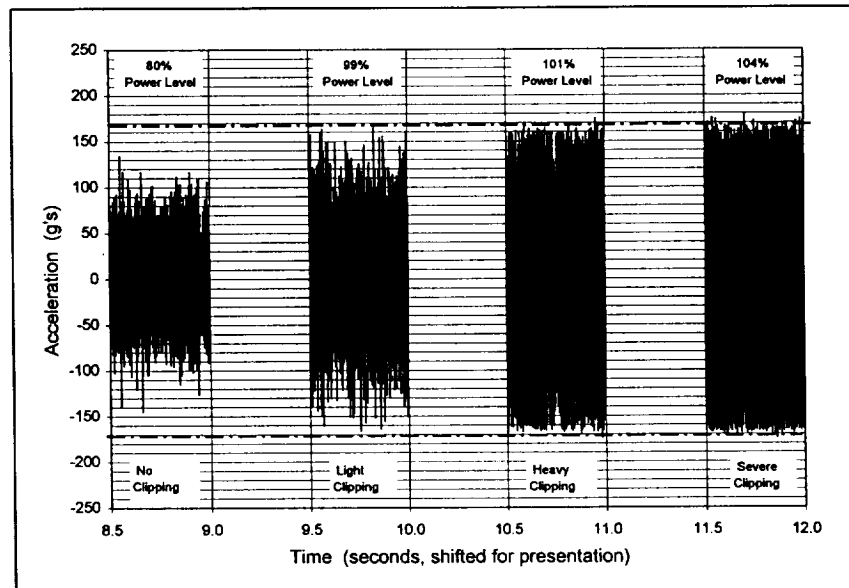


Figure 12. 7290a-100 accel low frequency signal quality for several engine power levels. Shows degree of clipping with increasing vibration level. Data digitized at 40,000 sps. Instantaneous Time Histories for 80%, 99%, 101%, and 104% power levels.

SUMMARY AND CONCLUSIONS

Measurements of low frequency dynamic accelerations generated by the SSME are difficult because of the severity of the engine environments. A review shows that there are a variety of approaches that can be employed that have the potential to improve low frequency measurement quality.

It has been shown that low frequency acceleration measurements on the SSME can be improved with the use of a higher sensitivity accelerometer, the Endevco Model 7290a-100. This accelerometer has 15 times the measurement sensitivity of the currently used accel. Its high measurement sensitivity combined with low natural frequency, high sensor damping, cryogenic capability, and capacity to survive high shock levels are significant characteristics that are instrumental in its ability to reduce low frequency noise. A PSD noise level reduction of 100:1 at low frequencies has been demonstrated compared to Rocketdyne's standard use accel, the Endevco Model 7704-M6.

The resonant frequency of the 7290's sensing element is low (approximately 4500 Hz) compared to the 36,000 Hz of the 7704). This limits its measuring frequency range from 0 to 1000 Hz. By comparison, the 7704 is capable of measuring frequencies up to 10,000 Hz..

Laboratory tests have been conducted on the 7704-M6 and 7290a-100 accels. These accels were subjected to a wide range of cryogenic temperatures, ice, frost, and moisture while simultaneously being excited by an environment of strong random vibration. However, it was not possible to reproduce the severity of actual engine operating environments. In particular, the

intensity of the SSME's high frequency vibration levels could not be achieved.

Measurements have also been acquired during engine operation ground tests. During these tests the 7290a-100 accel revealed a design weakness. An internal wire was found to have a resonant frequency low enough to be excited and driven to failure by turbopump blade wake vibrations. Modification of wire length has eliminated this failure mode.

Additional measurements during engine operation indicated an apparent lack of consistency of the low frequency noise floor quality of the 7290 accel. Further investigation revealed this apparent lack of consistency is actually an amplitude range limitation of the accel. As the intensity of random vibration level increases up to and beyond the 7290's range limit, the degree of amplitude peak clipping also increases. This results in proportionally degraded noise floor quality. However, when operating in less severe environments, the 7290 has provided consistently excellent output.

RECOMMENDATIONS

The Endevco Model 7290a-100 accelerometer has the potential to greatly improve the quality of low frequency measurements in severe environments similar to those of the SSME. However, amplitude range limitations of this accel need to be addressed. Increasing the accel's amplitude range capability should be pursued. Additionally, external isolators should be developed to minimize exposure of this accel to high frequency vibrations. Also, to permit measurements on components that transport liquid hydrogen, thermal isolation should be developed.

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